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## Qassim Abdullah/ Jeff Lovin- Woolpert, Inc

**The Role of Public and Private Partnership in Fostering New Lidar Sensors & Technologies: The Woolpert Experience**

Recent advances in LIDAR technology, specifically new designs based on very sensitive detectors and focal plane array receivers offer unique possibilities for wide area acquisitions of dense LIDAR point clouds. Advancing such new LIDAR technologies from the blue print phase to a productive system requires close involvement and coordination between private firms and public agencies which are interested in a flawless performance of such new LIDAR systems. Woolpert fostered the development of single photon LIDAR (SPL) and involved in evaluating the performance of the Geiger mode LIDAR (GML). Working with the US Army Geospatial Center (AGC) and the USGS National Geospatial Program (NGP), Woolpert developed strategies to collect and process lidar data using the SPL and GML. In the same time that new LIDAR technologies emerging slowly to the market, the current linear mode LIDAR is witnessing a technical revolution in terms of improved acquisition parameters, increased points density, and improved data quality and accuracy which is something we need to foster as well. The presentation will shed the light on the role of the private/public agencies partnership in bringing advancements in LIDAR technology to serve national programs and to demonstrate the continuous drive to develop new strategies to mitigate data productivity, quality and accuracy.

*Dr. Qassim Abdullah is an accomplished scientist with more than 40 years of combined industrial, research and development, and academic experience in analytical photogrammetry, digital remote sensing, and civil and surveying engineering. His current responsibilities include designing and managing strategic programs to develop and implement new remote sensing technologies focused on meeting the evolving needs of geospatial users. Currently, Dr. Abdullah is a lead research scientist and a member of Woolpert Labs team. In addition, Dr. Abdullah serves as an adjunct professor at the University of Maryland, Baltimore County and at Penn State teaching graduate courses on UAS, Photogrammetry and Remote Sensing. His latest accomplishments include evaluating and introducing the Geiger and single photon LiDAR to the geospatial industry and leading Woolpert research activities in the field of Unmanned Aerial System (UAS), its sensor calibration, and its workflow development. Dr. Abdullah obtained his doctorate and master degrees in photogrammetry from the Civil Engineering Department at the University of Washington in Seattle. Dr. Abdullah publishes a monthly column "Mapping Matters", in the American Society for Photogrammetry and Remote Sensing (ASPRS) journal PE&RS. During 2017, Dr. Abdullah was elected as a Fellow in the ASPRS in 2017 and he is the recipient of several prestigious awards such as the ASPRS 2010 Photogrammetric Fairchild award, the ASPRS Outstanding Service award for publishing the monthly column "Mapping Matter" for more than 10 years, the ASPRS Presidential Citation award in recognition to his contributions in co-authoring the new "Positional Accuracy Standards for Digital Geospatial Data", and the ASPRS Outstanding Workshop Instructor award. Dr. Abdullah is a certified photogrammetrist by ASPRS and licensed professional surveyor and mapper with the states of Florida, Oregon, Virginia, and South Carolina. He is also a certified thermographer by the FLIR Infrared Training Center and a Certified GEOINT Professional in Remote Sensing and Imagery Analysis (CGP-R) by the United States Geospatial Intelligence Foundation (USGIF).*

*Jeff Lovin is Senior Vice President and Managing Principal of the Government Solutions Market at Woolpert, a national geospatial, design, and engineering firm headquartered in Dayton, Ohio. Mr. Lovin has spent his entire 30-year career in the geospatial profession at Woolpert, where he has developed a diverse technical background as well as project management skills, senior leadership expertise and advocacy experience. Mr. Lovin has been integral to Woolpert's integration of leading-edge technology while also playing a critical role in the development of proprietary software and technology that also positions the firm as a leader in geospatial solutions.*
*Over nearly three decades, he has been involved with and oftentimes served in leadership roles for professional organizations including; MAPPS, ASPRS, COGO, and NGAC. Mr. Lovin has worked closely with federal clients not only related to contracts and programs but also to develop strategies and identify funding sources. He has also supported a number of universities in the development of their geospatial programs to advance the geospatial profession*

## Amit Angal, SSAI Inc.

**Cross-calibration of the reflective solar bands of Terra MODIS and Landsat 7 Enhanced Thematic Mapper Plus (ETM+)**

The Terra MODIS and Landsat 7 ETM+ have been successfully operating for over a decade producing high quality scientific measurements. This study evaluates the calibration consistency of the spectrally matching reflective solar bands of the two instruments. The Terra spacecraft follows Landsat 7 by approximately 30 minutes therefore facilitating a same day observation of a given target on the earth's surface. To further minimize the uncertainties associated with the differences in the overpass times, pseudo-invariant calibration sites (PICS) from the North African desert were chosen for this study. The characteristics of these PICS are well understood, in terms of its temporal, spatial, and spectral characteristics. Additional corrections for the atmospheric and site's bi-directional reflectance distribution function and other atmospheric variations, primarily water vapor, were also considered. Furthermore, a correction for the mismatch in the relative spectral response between the two instruments is also accounted for. The Terra MODIS Collection 6 level-1B products and the ETM+ Collection-1 same-day calibrated images over the PICS were chosen to evaluate the temporal stability of each instrument (and spectral band), as well as the agreement between the two sensors. While the long-term stability of each instrument (BRDF normalized top-of-atmosphere reflectance) is observed to be within 1%, disagreement, particularly in the SWIR channels is observed between the two instruments. A preliminary result from an independent validation using vicarious measurements is also presented in this paper.

*Amit Angal received a M.S degree in Electrical Engineering from South Dakota State University, Brookings, SD in October 2005. He is currently a Senior Optical Engineer with Science Systems and Applications, Inc., working with on the radiometric characterization and calibration of remote sensing instruments. He is primarily involved with the on-orbit calibration of the reflective solar bands of the MODIS instruments on board the Terra and Aqua missions. Mr. Angal has also supported the CLARREO Mission Preformulation activities in the reflective solar spectrum. He currently supports the JPSS-1/2 VIIRS instrument prelaunch characterization. His research interests include sensor cross-calibration and validation using pseudo-invariant desert sites.*

## Sara Bahloul-Planet

**High cadence stability of Planet Dove imagery – An evaluation for agricultural remote sensing applications using the NDVI**

Planet mission 1 delivers 4 band multispectral images of the whole earth every day. This high cadence opens the doors to various new applications. Important fields of applications are found in agriculture, forestry and others.

This proposed presentation evaluates the stability of the radiometric response of the different satellites to be used in a high cadence time series using the Normalized Difference Vegetation Index to proof that the stability of this index calculated from planet dove data is comparable to the stability of the same index calculated based on other missions like Sentinel 2, Landsat 8 or RapidEye.

*Sara Bahloul holds a Bachelor degree in Mathematics from the University of Bonn, Germany and a Master degree in Geodesy and Geoinformation Science from the Technical University Berlin, Germany. She is a Calibration & Validation Engineer at Planet in Berlin, Germany, helping to take care of the overall calibration and validation and all related tasks for the RapidEye satellite constellation of five identical optical multispectral imaging satellites and the growing Dove constellation.*

## Kevin Boyle, *NGA*

**Planet Doves-15 Day Landmass Coverage Assessment**

The National Geospatial-Intelligence Agency (NGA) Image Quality and Utility (NIQU) division evaluates civil and commercial remote sensing systems for the Department of Defense and Intelligence Community. NIQU performed an imagery coverage assessment on Planet Dove Imagery. The Assessment was designed to quantify the percentage of Earth land mass imaged by the Planet constellation over a 15-day period. NIQU exclusively tested Planet 4Band Basic imagery for this assessment over the time period spanning January 01—January 15, 2017. NIQU's results are in line with Planets internal testing produced for the similar time period. The results of the NIQU test are being used a proof of concept for potential follow on studies in which the Planet constellation could be tested in its entirety. (Approved for Public Release, Case 17-412).

*Kevin Boyle is a System Engineer supporting NGA's Image Quality and Utility Office (NIQU). He has recently supported NGA assessments of commercial small imagery. Kevin has 10 years' experience as an Air Force Imagery Analyst and 8 years' experience as a system engineer. Kevin received a M.S. degree in remote sensing and geographic information systems from Northeastern University.*

## Paul Bresnahan, *NGA/IAI Corp.*

**Kompsat-3A Imagery Absolute Geolocation Accuracy Evaluation**

The National Geospatial-Intelligence Agency (NGA) Image Quality and Utility (NIQU) division evaluates civil and commercial remote sensing systems for the Department of Defense and Intelligence Community. A major component of evaluation is the assessment of absolute geolocation accuracy. NIQU received Kompsat-3A images from SI Imaging Services and compared them to ground-surveyed check points of quantify geolocation accuracy metrics and graphically present the errors (Approved for Public Release, Case 17-413)

**Planet Dove Constellation Absolute Geolocation Accuracy, Geolocation Consistency, and Band co-Registration Analysis**

The National Geospatial-Intelligence Agency (NGA) Image Quality and Utility (NIQU) division evaluates civil and commercial remote sensing systems for the Department of Defense and Intelligence Community. Key elements of the Planet Dove imagery assessment include absolute geolocation accuracy (7/14/2016 to 1/20/2017), geolocation consistency (8/25/2016 to 1/25/2017, and band co-registration (7/27/2016 to 1/10/2017). NIQU estimate the absolute geolocation accuracy of unrectified Doves by comparing imagery-derived coordinates of common points measured in stacks of orthorectified images over the same locations. NIQU quantified the level of band co-registration for 4-band Doves images using a phase correlation matching technique. (Approved for Public Release, Case 17-411).

*Paul Bresnahan is a contractor supporting commercial satellite imagery geolocation accuracy evaluations for the National Geospatial-intelligence Agency (NGA). He has led or contributed to geolocation accuracy assessments of IKONOS, Quickbird, OrbView-3, EROS-A, EROS-B, SPOT-5, Radarsat-2, Cosmo-Skymed, TerraSAR-X. RapidEye. Kompsat-3, WorldView-1, WorldView-2, and GeoEye-1. He received an M.S. degree in Geodetic Science (Photogrammetry track) from the Ohio State University and a B.S. degree in Aeronautical/Astronautical Engineering from the University of Illinois at Urbana-Champaign.*

## Andreas Brunn- RapidEye

**Absolute Radiometric Calibration of the RapidEye Constellation – Adding RadCalNet to the workflow, lessons learned and results**

Since more than 8 years the RapidEye Constellation delivers high quality and well calibrated multispectral remote sensing data. Absolute calibration is done since 2009 with a growing number of vicarious calibration sites.

In 2016 Planet started to be a beta tester for RadCalNet. The proposed presentation describes the approach used to add RadCalNet data to the previous calibration procedures and shows the results achieved with this addition.

*Andreas holds a Diploma in Physical Geography (Dipl.-Geogr.) from the University of Wuerzburg, Germany and a PHD in remote sensing from Technical University of Clausthal, Germany.*

*Andreas Brunn is the manager of the calibration and validation group for the RapidEye constellation at Planet in Berlin, Germany. He and his team is responsible to oversee all calibration and validation tasks of the RapidEye satellite constellation of optical multispectral satellites and deliver support for all image quality and image accuracy questions for the Dove and Skysat constellation at planet.*

## Jon Christopherson - USGS EROS/SGT Inc.

**"New Space Explosion" and Earth Observing System Capabilities**

This presentation will describe recent developments in spaceborne remote sensing, including introduction to some of the increasing number of new firms entering the market, along with new systems and successes from established players, as well as industry consolidation reactions to these developments from communities of users. The information in this presentation will include inputs from the results of the Joint Agency Commercial Imagery Evaluation (JACIE) 2017 Civil Commercial Imagery Evaluation Workshop and the use of the US Geological Survey's Requirements Capabilities and Analysis for Earth Observation (RCA-EO) centralized Earth observing systems database and how system performance parameters are used with user science applications requirements.

*Jon Christopherson works at the USGS EROS Center as a contractor with SGT, Inc. With degrees in Electrical Engineering and Space Studies, he has worked with ground, airborne, and space-borne electro-optical sensors for over twenty-five years in various defense, aerospace, and civil programs, both domestically and internationally. He currently is supporting the USGS in the ongoing calibration of Landsat sensors, compiling information on remote sensing systems, assessing the capabilities of satellite and aerial data, and other tasks across the broad spectrum of remote sensing.*

## Chris Comp - DigitalGlobe Inc.

**WorldView-4 Instrument Performance and DigitalGlobe Constellation Accuracy Update**

DigitalGlobe launched the WorldView-4 satellite in November 2016. Orbiting at an altitude of 617 km the instrument is capable of 31 cm Panchromatic resolution and 1.24 m Multispectral resolution imagery. This presentation will describe the geometric and radiometric calibration of the WorldView-4 instrument. The post-calibration geometric and radiometric performance were rigorously evaluated and results will be shown. Finally, geometric accuracy of the entire DigitalGlobe constellation has been compiled for the prior year and will be presented for each satellite system

*Dr. Chris Comp is a Technical Fellow at DigitalGlobe, where his work has focused on precise attitude estimation, sensor calibration, and geometric modeling and analysis for the past 15 years. He has experience with the QuickBird-2, WorldView-1, 2, and 3 and 4 satellite systems, from conceptual design to launch and calibration of navigation and optical sensor systems. Prior to that, his work focused on algorithms and technology for GPS-based navigation of aircraft and satellites. He has a B.S. degree in Aerospace Engineering from the University of Arizona, a Ph.D. degree in Aerospace Engineering Sciences from the University of Colorado, and a Post-Doctorate from Stanford University*

## Mary E. (Becky) Cudzilo- Surrey Satellite Technology US LLC

**A Small Satellite Piggy-Back Calibrator (PBR) Enabling Accurate Absolute Radiometric Calibration**

This presentation discusses the results of a study regarding the development of an absolute radiometric calibration concept for an Earth imaging instrument in low-Earth orbit (LEO). The study considered in-flight calibration of imaging radiometers operating in both the solar spectral region and the thermal infrared (TIR) spectral regions to support a Landsat-8 compliant spacecraft. This small calibration instrument is a "piggy-back" radiometer (PBR) imaging the same Earth scene covered by the main instrument and measuring Earth radiance with enhanced accuracy and confidence levels. Precise knowledge of Earth radiance generated by the PBR would be used to provide calibration for the main instrument. The PBR fits within a small size, mass and power profile. The total volume of the PBR allows it to be easily mounted on the same deck with the main instrument. By removing the need for onboard calibration references that fill the main instrument aperture, the main instrument volume and mass are reduced, while improving the accuracy of absolute calibration. Analysis in the study demonstrated that transferring the calibration from the PBR to a main imaging instrument can be achieved in an operational manner, incurring minimal uncertainty. The operational cost of routinely performing the calibration is virtually zero since the necessary imaging will be occurring anyway, and the processing can be entirely automated. It also reduces the amount of pre-launch and ground calibration necessary for the main instrument.

*Becky Cudzilo is a senior systems engineer working with Surrey business development and sales personnel to create satellite designs for presentation to clients. She serves as the liaison between the Surrey US and UK offices focusing on the planned NovaSAR medium-resolution, S-band synthetic aperture radar mission along with multiple mission data sales activities. Current projects include reflectometry and remote sensing video data processing along with space situation awareness collections. Becky worked with Surrey as an engineering consultant for five years before becoming an employee in 2013. Her background in systems engineering includes work on numerous aerospace programs for GeoEye, InSequence Inc., ITEC Inc., DigitalGlobe Inc., and Lockheed Missiles and Space. Becky earned a bachelor of science in electrical engineering from the University of Tennessee at Chattanooga and a master of science in electrical engineering/image processing from the University of Wyoming.*

## Ellis Freedman- Serious Science, LLC

**Using the Constant MTF Interpolator to Reduce Aperture Size in Imaging Systems**

It has already been shown in previous JACIE presentations that the Constant MTF (CMTF) interpolator could reduce or eliminate the degradation and variability of the MTF when resampling an image. In a 2016 study funded by the NASA Earth Science Technology Office (ESTO), it was shown that replacing traditional resamplers with the CMTF had the potential to enable a reduction in the aperture size of imagers for the Sustainable Land Imaging (SLI) program. This presentation summarizes some of the results of trading aperture size against resampler type from that study.

*Ellis Freedman has a B.S. from Temple University and an M.S. from Northeastern University, both in physics, and over 39 years' experience in remote sensing. In 2010, after 27 years with Lockheed Martin Co., he left the position of Fellow to form his own consulting firm, Serious Science, LLC. He has been Chief Engineer for the calibration of electro optic sensors and the processing of raw data into imagery for large government and commercial remote sensing systems. As a project lead, he has designed the high level architecture for large data processing systems and developed mathematical algorithms and modeling tools for the correction, enhancement, and exploitation of imagery, and the characterization, detection, and removal of artifacts and noise. He has also led the development, integration, and implementation of a variety of visible, infrared, radar, multispectral and hyperspectral hardware and software systems. He is currently focusing his efforts on providing technical and systems engineering support to commercial imaging systems and pursuits of future civil remote sensing programs.*

## Jorge Gil- Deimos Imaging, an UrtheCast company

**DEIMOS-1 Cross-calibration with Landsat and Sentinel-2**

The DEIMOS-1 satellite, owned and operated by UrtheCast through its subsidiary Deimos Imaging, is an Earth observation system designed to expand Landsat's capabilities and applications. DEIMOS-1 has provided the USDA with the bulk of the imagery used to monitor the crop season in the Lower 48 since 2011.

DEIMOS-1 measurements have a tight correlation with Landsat missions. This correlation is achieved thanks both to design and cross-calibration. The DEIMOS-1 sensor, SLIM6-22, has three bands whose spectral response is very close to Landsat-7 ETM+ 4, 3, 2 and Landsat 8 OLI 3 and 4 bands. Moreover, the spatial resolution is very similar on these bands (22m GSD for DEIMOS-1 and 30m GSD for Landsat at nadir).

These DEIMOS-1 features, combined with a swath >600km and the capability of acquiring up to 5,000,000 km2 per day, increases the availability and usability of Landsat-class imagery.

ESA's Sentinel-2 mission is currently complementing Landsat's coverage and applications, creating a proper environment for synergistic opportunities, which anyway need a continuous effort in the harmonization of both data sources.

Deimos Imaging is permanently conducting cross-calibration procedures to maintain the DEIMOS-1 data harmonized with Landsat's. Some of them have been presented in previous

JACIE workshops. In accordance with the aforementioned harmonization effort, we started developing a cross-calibration procedure with Sentinel-2 after the first satellite of the constellation (Sentinel-2A) became operational in late 2015.
This work starts by providing a summary of the current health and orbit status of DEIMOS-1, which is now in its eighth year in space. We will then provide an update of the status of the *cross-calibration of DEIMOS-1 with Landsat-7 and Landsat-8, together with the description of the DEIMOS-1/Sentinel-2 cross-calibration procedure and its results.*
*After drawing the conclusions, we will go through a brief review of how the use of a new generation of multispectral sensors opens new perspectives in the Earth Observation field, representing an opportunity in the cross-calibration and data fusion of the current sensors from the PanGeo Alliance (12 operational optical satellites) as well as of the future UrtheDaily Constellation.*

Jorge Gil has a degree in physics from the University of Valladolid (Spain). In 2005 he joined the Remote Sensing Laboratory of the University of Valladolid (LaTUV) where he specialized in image processing, working with MODIS, Landsat, NOAA, Meteosat and other earth observation systems. In 2006 he was hired by the Earth Observation company Deimos Imaging, which is now a subsidiary of UrtheCast Corp. (Canada) which operates, manage and exploit the Deimos-1 and Deimos-2 satellites. He is responsible of the image processing chain and the calibration activities.

## Dennis Helder - USGS EROS

**Landsat 8 OLI and Sentinel 2 Data Interoperability: Looking from the Calibration Perspective**

Landsat 8 OLI was launched in 2013, Sentinel 2A MSI was launched in 2015, and Sentinel 2B MSI was launched just this year. Together, these satellite systems form a high-performance trio of instruments for science-grade observations of the Earth. Temporally dense time series of Earth observations can be formed from these data, but the question remains open as to how well data from these sensors can be integrated into a seamless set of information. The purpose of this paper is to first take a look at how well the instruments are cross-calibrated and then assess how well data harmonization can be accomplished by assessing performance using well understood calibration sites.

Landsat 8 OLI has been in operational use the longest of the three sensors and, over its entire lifetime of 4+ years has shown a measurable degradation of only 1%. This has occurred in band 1 which is in the deep blue portion of the spectrum; all other bands have essentially shown no appreciable change. Sentinel 2A has experienced several calibration updates in its 2+ year lifetime which have kept data from the instrument on a consistent calibration scale. It is obviously too early to provide an assessment of Sentinel 2B.

Initial efforts evaluating the cross-calibration of these instruments have been performed by a number of teams, several publications are available and will be referenced. Details of the cross-calibration work done by USGS EROS and South Dakota State University will be presented here. For the most part, these efforts indicate a cross-calibration consistency between the two instruments on the order of 3% or less for equivalent bands.

Finally, time series will be presented that merge the data from all three sensors over well-known calibration sites both in the Sahara, as well as in the United States. In forming these time series, differences between the sensors were modeled and taken into account—especially with respect to spectral differences. Results show that the sensors produce data that are very consistent with one another over known targets. However, when the spectral properties of the target are unknown, larger uncertainties creep into the data. Then extent of these uncertainties will be presented so that users of the combined data sets will have some estimates of how large these may be.

*Dr. Dennis Helder has been involved with the characterization and calibration of spaceborne and airborne remote sensing imaging systems for over 25 years. Initial work focused on characterization and removal of radiometric artifacts of the Landsat TM and MSS sensors. More recent work has emphasized development of vicarious radiometric calibration approaches for a variety of optical remote sensing systems as well as on-orbit point spread function estimation. He is currently Associate Dean for Engineering Research and Distinguished Professor of Electrical Engineering at South Dakota State University and is also on detail to USGS EROS as a Senior Calibration Advisor*

## Dr. Shawna Johnson- Global Marketing Insights, Inc

### Calibration and Delivery of Global-Scale Commercial Imagery in a Cloud-Based Computational Platform Optimized for Analysis such as Temporal Regressions, Machine Learning, and Change Detection

Continuing improvements in computing capabilities and performance is driving rapid changes and improvements in commercial sensor development, imagery processing and storage technologies. Multi-decadal remote sensing datasets at the petabyte scale are now available in commercial clouds, with new satellite constellations generating petabytes/year of daily varying resolutions of global coverage imagery.

Cloud computing and storage, combined with recent advances in machine learning are enabling understanding of the world at a scale and at a level of detail never before feasible. This presentation will discuss briefly additional technology impacts to commercial remote sensing in the next decade and focus on:

- commercial data processing at terabyte rates in the cloud using multi-modal sensor data utilizing calibrated, georeferenced imagery to build videos of the Earth at varying temporal and spatial resolutions which include the data processing and automated analysis, with scripts detecting, importing and processing daily imagery from NASA, USGS, NOAA, ESA and Planet Labs internet servers within minutes of data availability (keeping in mind the technology is data stack agnostic)
- utilizing machine learning to demonstrate ways in which a global scale automated data platform enables quick prototyping of various commercial satellite imagery analysis algorithms with multi-sensor data, from general land use land cover classification and fast mosaics to change and object detection.
- general data flow and computational aspects required for prototyping such algorithms using open source software and cloud computing resources
- a system architecture which demonstrates automated:
    - continual ingest

- geo-referencing
- cloud removal
- quality assessment
- analysis of petabytes of satellite imagery [served via WMS and REST access leveraging a proprietary code base of cloud-native services for leading open source scalable technologies with Docker containers running on scalable clusters of virtual machines (Ubuntu Linux base machines) across multiple data centers, which run in both Google and Amazon commercial clouds].
- standard library usage with GDAL and kakadu (JPEG2000) for file access to remote sensing imagery
- data and analysis delivery to customers [via web-based APIs and high-performance WMS layers for easy consumption and inclusion in  in open source and/or widely used proprietary geographical information systems].

More important than the technology utilized to serve and analyze commercial imagery is the preparation of the data or the refinement of raw imagery to analysis-ready format.  This presentation will also discuss the global scale processes as each image is retrieved, is uncompressed, and the image metadata is parsed and the raw pixel information is converted into meaningful units. Imagery delivery and storage as appropriately sized pieces using a consistent equal-area world-wide tiling of the sphere, (with any necessary co-ordinate transformations and data compressions) with follow on access will be demonstrated. Finally the use of imagery for automated extraction of high-level business intelligence will be demonstrated through proprietary automated analysis models.

*Dr. Shawana Johnson, GISP serves the geospatial industry as CEO to an international client base providing Geospatial Business Intelligence Expertise™ for Geospatial Data Interoperability Programs and enabling federally developed technology transfers to the private sector for societal benefit; specializing in the applications areas of Agriculture and Water Resources and technology areas such as global scale satellite imagery cloud analysis and delivery and the internet of things focused on geospatial technologies. She oversees the development of Geospatial Plans for: strategic sales and marketing as well as customized marketing research studies for the US government and global commercial organizations. She obtained her Doctorate degree in 1998 from The Weatherhead School of Management, Case Western Reserve University, and Cleveland, OH. Dr. Johnson provides Peer Review for: the NASA team for Group on Earth Observations and the GEO Secretariat as well as serves on a variety of geospatial organization and commercial boards.*

*Dr. Steven P. Brumby is Co-Founder and Chief Science Advisor of Descartes Labs, a venture-backed start-up spun out of Los Alamos National Laboratory in 2014 focused on understanding agriculture, natural resources and human geography using machine learning and satellite imagery.  Previously, Steven was a Senior Research Scientist at Los Alamos National Laboratory working on image, video and signals analysis for space and earth observation missions. He received his Ph.D. in Theoretical Physics at the University of Melbourne (Australia) in 1997. Dr. Brumby recently moved to Washington DC and serves also as a Senior Fellow in World Resources Institute; Food, Forests and Water Programs.*

## Arin Jumpsat-Planet

**Using lunar imagery to track long term trends within a fleet of satellites**

Captures of the moon at different phases of the cycle, every month are an essential part of Planet's radiometric calibration and validation program [1]. Since October 2016, each satellite in the Planet constellation images the moon every month at three phase angles in both the waxing and waning parts of the lunar cycle. The radiance measurements from this data are compared to a numerical model of the Moon's radiance, an implementation of the ROLO model [2]. The tasking, acquisition and processing of moon shots is an automated process and during 2017 will be scaled to over a hundred satellites. This presentation will describe the two primary uses of this dataset. It is used for the calculation of the relative accuracy of the entire fleet without the effect of atmosphere. This allows us to track the radiometric consistency of the imagery captured by the fleet. It is also used to monitor temporal trends for each satellite individually, track any changes in the radiometric performance and correct for them.

*Arin Jumpasut joined Planet in 2014 and currently works on the Calibration and Validation team. His main research topics are the radiometric calibration and validation of the Dove satellites including the coordination of calibration related satellite maneuvers with satellite operators. He completed his DPhil at the University of Oxford in 2010 in the Solid Mechanics and Materials Group of the Department of Engineering Science. This was done in collaboration with Rolls Royce Aeroengines and concentrated on photogrammetry of high strain rate experiments for bird strike and fan blade off events. After this and prior to joining Planet, he was at Samsung Electronics in South Korea and worked on computer vision algorithms for commercial applications. This included development of object extraction algorithms, implementation of gesture detection systems and image processing research for stereoscopic cameras and displays.*

## Minsu Kim- USGS EROS / SGT Inc

**Atmospheric Correction of OLI Image Using Aerosol Optical Thickness Based on Scene Derived endmembers**

An atmospheric correction algorithm for the Landsat 8 OLI (Operational Land Imager) data is proposed. The standard aerosol inversion algorithm for OLI data was developed by NASA. It utilizes LUMs (look-up maps) of the linear regression coefficients between normalized difference index and the blue to red reflectance ratio. The last 10 years of MODIS data was used to produce regression results. However, the LUMs are available in the CMG (climate modeling grid) resolution of 0.05 degree, which is too coarse to be used properly for 30m OLI imagery. It is the specific approach to constrain the ground reflectance in order to estimate the amount of aerosol. In this study we propose a different approach based on the optimization of TOA (top of the atmosphere) reflectance using a standard reflectance model. The surface reflectance is handled as a linear combination of endmember spectra extracted from the scene. In this manner we can avoid the use of LUMs. The suggested algorithm approximates the semi-analytic mathematical model of the atmospheric reflectance and scattering transmittance LUT that were generated from 6SV radiative transfer model.

*Cornell University, PhD*
*Radiative transfer, Lidar, Hyperspectral*
*USGS Landsat 8 OLI atmospheric correction*
*USGS 3DEP LIDAR accuracy assessment*

## Alex Kudriashova- Astro Digital

**How imagery quality impacts analysis**

In this talk we will discuss the Landmapper approach and why it's critical to start with the business problem you're
trying to solve and design the satellite system to match. At Astro Digital, we have seen a demand for global scale trend analysis - for companies to investigate how their assets change over time, when and where there is risk. Building the technology solution to answer this opportunity requires a sensor that produces science quality data; operational capacity for persistent and reliable imaging; calibration program to normalize across images and spacecraft; processing infrastructure and algorithms to ask questions of the data source. We also needed to keep costs in balance so that we can afford to place value on the information not individual pixels. As a new space company building an Earth observation system, we have the huge advantage of standing on the shoulders of decades of academic research, government programs, and commercial applications. By harnessing the collective knowledge and resources, we have been able to design a system to begin tapping into the trend analysis opportunity.
USGS

*Alexandra leads data integration at Astro Digital - a platform for fast and easy access to satellite imagery; was a co-founder of ImageAiry - online marketplace for satellite imaging services; brought Computer Science and Technical Leadership expertise from MIT; worked at B2B software solutions at Dell Inc; Alex is interested in Open Source, Big Data, and Business Intelligence .Her current projects are Machine Learning and Artificial Intelligence for crop classification, Pattern recognition in farming process for commodity crops, Automatic detection of buildings of time series of mid-resolution imagery (NGA hackathon winner)*

## Michele Kuester- DigitalGlobe, Inc.

**Absolute Radiometric Calibration of the DigitalGlobe Constellation, including CAVIS and the new WorldView-4 Sensor**

DigitalGlobe Inc. at Westminster, CO, USA, uses reflectance-based (vicarious) calibration as its primary calibration approach. Ground-based surface reflectance data of specialized tarps laid out at our site in Longmont, CO, USA, are the main measurement in this on-orbit approach. Various atmospheric measurements are also important. These data are collected at the same time as the image acquisition of the intended sensor under test and then input to a radiative transfer code that computes predicted at-sensor radiances for comparison. In a single season data are collected over as many days as are available (contingent upon weather and access of the sensor to the site) to sample the instrument parameters that affect the radiometry including time delay integration settings, exposure levels, scan direction, and position of the target on the focal plane. Several data points are collected throughout a calibration season over the well-characterized targets. These data are used in a linear regression to determine an adjustment to the pre-launch absolute calibration factor that is currently reported in the supporting documentation that is shipped with imagery.

This paper describes the work done in the 2016 calibration season to improve the vicarious calibration methodology used by DigitalGlobe to augment the absolute radiometric calibration coefficients of the DigitalGlobe constellation. The constellation includes WorldView-4, WorldView-3 (including CAVIS), WorldView-2, GeoEye-1, and WorldView-1. Improved reflectance modeling of the targets and the use of a NASA GODDARD AERONET station with closer proximity to our site than has been used in the past allowed for improved confidence in the in-situ measurements. Future improvements in place already for the current vicarious season will also be discussed. These include a more robust measurement of the reflectance of the surrounding ground cover (a measurement included in the radiative transfer code for scattering off of neighboring surfaces); and the use of both a sun photometer and shadowband radiometer for improved atmospheric modeling. New coefficients derived during the 2016 vicarious campaign are used to calibrate imagery over Brookings, SD, USA, and Railroad Valley, NV, USA, and are compared to in-situ measurements made by South Dakota State University and University of Arizona respectively.

The CAVIS sensor cannot be calibrated with the primary method, as the 20 meter square tarps are smaller than the 30 meter CAVIS ground pixel size. Instead, a model of top-of-atmosphere reflectance derived for the Libya-4 calibration site located in the Saharan Desert is used. In addition, calibrated WorldView-3 VNIR and SWIR bands can be used to transfer the primary calibration method to CAVIS over large homogeneous areas. Also, where coincident collects are available, comparisons can be made to other well-known sensors such as NASA's Landsat 8.

New recommended absolute radiometric calibration adjustment coefficients will be presented for all of the DigitalGlobe sensors. The current adjustment factors are also available at hyperlink. These are updated as the constellation calibrations are refined


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*Michele Kuester holds a Ph.D. and M.S. in atmospheric and oceanic sciences from CU Boulder and an M.S. in optical sciences and B.S. in Physics from University of Arizona. She started her educational journey with a B.A. in music production. Dr. Kuester has more than 15 years of experience in the Earth remote sensing field. An expert in space, airborne, and field-based Earth remote sensing, she lends this experience to the absolute radiometric calibration of the DigitalGlobe constellation of Earth observing sensors. Kuester's work at DigitalGlobe involves the management of vicarious campaigns for on-orbit monitoring of the radiometric performance of the DigitalGlobe constellation. In addition to Earth remote sensing and absolute radiometric calibration, her areas of expertise include ecological remote sensing, radiative transfer, and atmospheric dynamics. Prior to DigitalGlobe, she worked with the SDSU team supporting NASA on pre-launch radiometric characterization of both instruments onboard the Landsat Data Continuity Mission payload. Kuester helped develop the airborne platform and labs at NEON Inc. in Boulder, CO. While at Ball Aerospace, she led an initiative to develop and fly proof-of-concept Earth observing sensors and the team that designed the Ball Heliostat Test System*

## Donghan Lee- Korea Aerospace Research Institute

**Spatial Quality from Edge target imaged by KOMPSAT-3**

Spatial quality for the remote sensing satellite and the image data of it is controversial in how to measure it within the reasonable quantitative value. Generally, although RER, FWHM and MTF value at Nyquist frequency have been used for getting it, there aren't proper standard estimator and method to get it yet. As a part of the Geospatial standardization in CEOS WGCV IVOS and the previous presentation in JACIE 2016, this presentation shows the characteristics, some issues and relations of RER, FWHM and MTF by the KOMPSAT-3 image data with the Edge target worldwide.

*DongHan Lee was born in Seoul, South Korea. He received the B.S., M.S. and Ph.D degrees in Astronomy & Space science from Yonsei University, Seoul, in 1990, 1994 and 2011. He has been a chief engineer of the Calibration and Validation for the KOMPSAT series in Korea Aerospace Research Institute (KARI), DaeJeon, from 1995 to now. Dr. Lee is a specialist of the Radiometric and Spatial Calibration and Validation of the high resolution optical remote sensing satellite, and a head of Cal/Val & Data Quality Control team in KARI.*

## Dr. Steve Mackin- Surrey Technology Centre

**Automated radiometric calibration and data quality assessment for satellite constellations**

One of the biggest challenges of the huge increase in the number of available satellite systems is providing timely and high quality radiometric and data quality information. The ideal solution, especially in systems that show some level of instability is to derive the information required to calibrate the data and to improve the data quality from the images themselves. In this presentation we provide results of using a range of algorithms to assess SNR, instrument focus, relative gain and absolute calibration drift for a range of small satellite systems and for flagship missions Landsat 8 OLI and Sentinel 2A and 2B. For these flagship missions we show how by using single heterogeneous images we can detect very low level calibration variability not seen using onboard calibration devices.

The overall conclusion is that it is feasible to determine both calibration and data quality measures from heterogeneous images at sampling intervals that exceed many on-board calibration devices and with an accuracy that in many cases is equal to or in some cases exceeds that of the current, commonly used calibration methods

*Dr Mackin has worked in Remote Sensing for over 30 years, initially in geological applications using hyperspectral data. He has worked for DLR in Germany, the British National Space Centre, and the Universities of Surrey in the UK and the Universidad Autonoma in Madrid. More recently he was Chief Scientist at DMCii and a Principal Research Scientist at the National Physical Lab in the UK. He has interests in remote sensing applications, instrument calibration and data quality and the true artificial intelligence systems (not the rubbish we currently call AI).*

## Andrea Minchella- Airbus Defence and Space

**A Copernicus CQC Harmonization Activity to Consider the Correction of BRDF Eeffects in VHR Optical Imagery.**

In the frame of the Copernicus Space Component Data Access (CSCDA), the Copernicus Coordinated data Quality Control (CQC), a service provided by ESA, is the component in charge of monitoring and assessing the quality of datasets and products contributing to the Copernicus Space Component. Whilst the Copernicus data providers retain responsibility for the quality of their products, the CQC has responsibility to ensure traceability of the quality information for the delivered data products. Through this unique perspective, the CQC has undertaken a number of harmonization initiatives. It is acknowledged that there is variability of technical terms, definitions, metadata, file formats, processing levels, algorithms, cal/val procedures etc. among products from different missions, suggesting the need for a strong, common effort of harmonization. One initiative in particular explores the Bidirectional Reflectance Distribution Function (BRDF), the need to apply BRDF corrections/modelling to VHR optical datasets, and consolidation of a common terminology relevant to the surface reflectance. Recorded reflectance may be strongly affected by the viewing geometry of the Sun-Earth-sensor constellation as well as the natural anisotropy of the observed surfaces (e.g. vegetation, soil, water, etc.). However, few studies have addressed the issue of operational compensation of BRDF effects within high spatial resolution sensors. Land surface anisotropy arising from non-constant observation and illumination geometries can cause significant variations in the surface reflectance unrelated to surface changes. These variations, which cause time series noise, can affect land surface analysis. The characterization of the viewing geometry and the surface anisotropy can be important for very high resolution multi-temporal optical imagery such as WorldView1/2/3, GeoEye-1, and Pléiades-1A/1B, because the acquisition agility of these missions allow image collection with a wide range of azimuth and elevation angles. With the aim to develop a harmonized approach to BRDF correction the CQC Team plans to foster a dialogue across the quality teams of all Copernicus data providers with focus on the following questions:

- Is it technically feasible and financially affordable to offer a standard reflectance VHR product which is corrected (or at least improved) for the surface anisotropy?
- Does the EO community and technologies have an overall degree of maturity (e.g. knowledge, algorithms, technical infrastructure, etc.) needed to address the issue of the BRDF?
- Is it possible to find synergies across Copernicus data providers?

*Andrea has more than 10 years of experience working in the field of Earth Observation data exploitation, mainly SAR image processing. He got an MSc in Electronic Engineering and a PhD in Geo-Information - EO Remote Sensing from the University of Rome Tor Vergata in Italy. His main line of research was focused on the joint use of microwave scattering models and SAR data for bio-physical parameters estimation, but he gained as well skills in InSAR-DInSAR techniques, optical-Xs medium and HR data processing, 3D GIS Virtual Reality. From December 2006 to May 2014, he had been working for the Remote Sensing Applications Consultants Ltd. at the European Space Agency-ESRIN, providing technical and scientific expertise for the development of ESA open source SAR toolboxes (NEST/Sentinel-1 and PolSARpro), SAR R&D projects and ESA Advanced Training Courses on Land Remote Sending. From June 2014 to November 2016, he had been working for the Satellite Applications Catapult, in UK, as SAR Specialist, with the main tasks to lead the exploitation of SAR data for a variety of projects within the commercial CEMS high performance cloud computing infrastructure at the Catapult. From December 2016, Andrea has been working as Earth Observation Analyst in the Intelligence department of Airbus Defence and Space, mainly supporting the Copernicus Coordinated data Quality Control service.*

## Tina Ochoa- DigitalGlobe, Inc.

### Development of an Empirical Model of the Libya-4 Saharan Desert Site that Utilizes DigitalGlobe Imagery That Are Calibrated by the Reflectance-Based Mmethod

DigitalGlobe uses a reflectance-based vicarious technique to calibrate its constellation of sensors, including WorldView-4, WorldView-3, WorldView-2, GeoEye-1, and WorldView-1. Traditionally this is accomplished using ground-based surface reflectance measurements taken in Longmont, CO, USA. These measurements can only be taken during the summer months when the weather permits. Worldview-4 launched in November 2016, and therefore could not initially be calibrated using this technique, prompting a new method to be developed for the initial calibration that does not depend on ground measurements to create calibration coefficients. This method involves creating and evaluating a bi-directional reflectance distribution function (BRDF) model of the pseudo-invariant calibration site (PICS) Libya-4 in the Saharan Desert. This desert site is well known for being homogenous and stable. Like the traditional approach, this process results in gain and offset coefficients for each band that are used to adjust the pre-launch absolute calibration factor.

To create the BRDF model, EO-1 Hyperion data was collected, spanning from 2009 to present, and used to compute a mean top-of-atmosphere (TOA) hyperspectral reflectance of the Libya-4 site. This reflectance curve is then modified by offsetting it to better fit the reflectance measurements of a well-calibrated overpassing sensor. A collection of such TOA absolute reflectances are assembled from each of the DigitalGlobe multispectral sensors with archived Libya-4 imagery. These data are used together to create a BRDF model of the calibration site. The model can then be evaluated at the sensor overpass look and sun angles to give a predicted at-sensor reflectance. Calibration coefficients can then be derived using a linear regression with the BRDF model predicted and sensor-measured reflectances. This approach has been used to calibrate WorldView-4, and the results will be presented here. It has also been applied to WorldView-3 and WorldView-2 for comparison and validation against the traditional ground-based method. The comparison is presented here using in-situ TOA spectrally-resolved reflectances provided by the Radiometric Calibration Network (RadCalNet) versus sensor-measured reflectances corrected by the most recent traditional coefficients derived during the 2016 vicarious campaign in Longmont, and corrected by the BRDF modeled coefficients.

*Tina Ochoa holds a bachelor's degree in astrophysics from the University of Colorado-Boulder. She performed her undergraduate research on the time domains of transient and variable stars, utilizing both remote and on-site optical telescopes. Ochoa has been working at DigitalGlobe the past two years as a part of the earth remote sensing group.*

*Here she focuses on the absolute radiometric calibration of the satellite fleet. She leads a team performing field campaigns for tracking on-orbit radiometric performance of the sensors, as well as works to improve uncertainties by innovating new methods of data analysis and atmospheric data collection.*

## Mary Pagnutti-Innovative Imaging and Research Corp

**Automated On-orbit Characterization of the DLR DESIS Sensor on the International Space Station**

This paper discusses the methods and approaches that will be used for automated quality assurance estimates of the DLR Earth Sensing Imaging Spectrometer (DESIS) sensor and derived data products. DESIS is a hyperspectral sensor, which provides up to 235 channels at a 2.55 nm spectral sampling, covering the 400-1000 nm spectral range and the first instrument being integrated with the Multi-User System for Earth Sensing (MUSES) platform on the International Space Station (ISS) by Teledyne Brown Engineering. At the ISS nominal 400 km orbital altitude, DESIS will provide 30 m ground sample distance data with a 30 km swath. The raw DESIS data will be archived, managed and converted to higher level products within an Amazon Web Services (AWS) cloud-based workflow. As part of the workflow, each scene will be analyzed by a set of quality assurance algorithms, which will estimate the in-flight spatial resolution and SNR of each scene. The Relative Edge Response (RER), and Modulation Transfer Function (MTF), when possible, will be estimated using naturally occurring edges found in the scenes. The SNR will be estimated over the dynamic range of the sensor using sparse methods. Geometric product accuracy will be compared to Landsat and other data sets. Since DESIS has not launched yet, examples of this capability will be shown using Hyperion, Landsat 8, NAIP and AVIRIS imagery.

*Ms. Mary Pagnutti holds a Master's of Science in Mechanical Engineering from the State University of New York at Stony Brook and has over 30 years of engineering experience ranging from large aerospace defense projects to civil remote sensing applications. From 1998-2007 Ms. Pagnutti supported NASA Stennis Space Center Earth Science programs where she helped to build a nationally recognized in-flight calibration/validation capability. In 2007 Ms. Pagnutti co-founded Innovative Imaging and Research, a company focused on imaging technologies and image quality.*

## Ray Perkins- Teledyne Brown Engineering

### The DLR Earth Sensing Imaging Spectrometer - Pre-Launch Status and Ground Calibration Update

The DLR Earth Sensing Imaging Spectrometer (DESIS), operated from the Teledyne Multi-User System for Earth Sensing (MUSES) will provide space-based Visible to Near InfraRed hyperspectral data to support scientific, humanitarian, and commercial objectives. The DESIS instrument will be the first commercially available, production class, space-based imaging spectrometer capable of delivering near-global coverage with long-term, high quality, high spectral resolution data. This will enable significant new research, expand the dimensions of humanitarian crisis response, and provide improved large-scale commercial hyperspectral analytic applications.

The DESIS instrument will complete final assembly and integration in mid-summer of this year, and then move into integrated system test and pre-launch calibration at the DLR facility in Berlin, Germany. The DESIS instrument is scheduled for delivery to the launch integrator in Q4, 2017. In-flight commissioning aboard the MUSES platform is planned for Q1-Q2, 2018.

This presentation will provide updates to the JACIE community on the current status of the DESIS flight and ground segments. The flight segment status will include results from ground testing and pre-launch calibration. The ground segment status will include status from image processing software integrated testing, as well as results from testing the algorithms for rolling shutter and smile correction of the DESIS instrument.

### Multi-User System for Earth Sensing (MUSES)

Teledyne Technologies will launch the Multi-User System for Earth Sensing (MUSES) platform in June, 2017. MUSES will attach to the International Space Station (ISS) and is designed to host up to four robotically-installed Earth-observing instruments to return data for commercial, scientific, and humanitarian uses.

Teledyne retains ownership of the MUSES platform and instruments, retains MUSES instrument data rights, and controls all platform tasking. The instruments and platform will be operated through the Teledyne Operations Center in Huntsville, Alabama, under a NOAA commercial imaging license. MUSES instruments are launched separately from the platform for robotic installation, significantly reducing instrument development time and supporting on-orbit instrument change-out. This approach enables support of both long-term operational instruments and short-duration technology readiness enhancement missions.

The inertially stabilized pointing platform features a two-axis gimbal and provides a 50° field of regard in both along-track and cross-track directions. The platform agility and the ISS orbit support weekly revisit opportunities, enable studies of diurnal variations, and provide varying target aspect angles to support investigation of bidirectional reflectance distribution function effects.

This presentation will provide updates to the JACIE community on the current status of the MUSES in-flight commissioning program. During commissioning, the Teledyne operations team will conduct performance testing, sensor subsystem characterization and calibration. We will provide updates on the MUSES time synchronization, platform stability, position and attitude determination, as well as pointing accuracy and knowledge.

*Mr. Perkins is the Business Development Manager for Geospatial Solutions at Teledyne Brown Engineering (TBE). In his previous position, he was the Chief Engineer leading the development of the ground segment for TBE's Multi-User System for Earth Sensing (MUSES). MUSES will launch in June 2017 and then be robotically installed on a nadir-facing berth of the International Space Station. The MUSES platform will host up to 4 earth-observing instruments and provide remotely-sensed data for commercial, scientific and humanitarian customers. Mr. Perkins joined TBE in 2004, supporting TBE's efforts to fulfill the nation's Vision for Space Exploration. During his tenure with TBE, he has led Systems Engineering, Modeling and Simulation, and Command and Data Handling teams supporting space launch vehicles and orbiting payloads.*

*Mr. Perkins has worked in the aerospace, defense, and technology sectors for 40 years. His prior experience includes managing the design, development and fielding of geospatial information systems as well as real time tracking, control and management systems for U. S. and international customers. Mr. Perkins has a Bachelor's of Science in Chemistry from Auburn University and a Master's of Science in Computer Science from the University of Alabama in Huntsville*

## Ajit Sampath- USGS EROS- SGT Inc.

### Lidar accuracy assessment methods

The Geometric quality of LIDAR data is an excellent indicator of the quality of data acquisition. Unfortunately, there are no consistent methods that are accepted as standard practice in the industry. This presentation proposes a consistent way to measure the inter-swath accuracy of LIDAR data, and research efforts by the USGS to develop quality assessment methods to determine 3D accuracy of very high resolution LIDAR data.

### Characterization of Planet data

This study presents a geometric, spatial and radiometric characterization of Planet Data. The Geometric characterization was performed over test ranges over Sioux Falls, SD, Salt Lake City, UT. The MTF characterization was performed over targets in Batuo, China. The radiometric characterization was performed using data gathered over test ranges in Libya and Egypt.

### Characterization of IRS (Resourcesat 1 and 2) data and Sentinel 3A/MODIS/VIIRS

The Eros data center is also processing and releasing data collected from IRS satellites over the US. Geometric characterization of the data collected by the AWiFS and the LISS-III sensors on these two platforms will be presented. Also a comparison of Sentinel 3A/MODIS and VIIRS data will be presented

*Aparajithan (Ajit) Sampath obtained his PhD in Geomatics Engineering from Purdue University. During his PhD, Ajit worked on many projects sponsored by the Indiana department of transportation and NASA. Ajit's thesis was on automatic segmentation of 3D point cloud data and generating topologically correct 3D building models. For the past 7 years, Ajit has been working as calibration engineer at the US Geological Survey's EROS data center. He has helped calibrate satellite remote sensing sensors, aerial cameras, and LIDAR sensors. Ajit's research interests include sensor modeling, quality assessment of data, feature extraction, linear and nonlinear optimization*

## Stephen Schiller-South Dakota State University

### Reflectance Calibration Using A Mirror-based Empirical Line Method

The empirical line method (ELM) in remote sensing is a very effective ground truth approach for calibrating image data to obtain reflectivity measurements of targets of interest directly from the sensor digital number (DN) response using in-scene radiometric targets having known Lambertian reflectance factors. The application, using diffuse reflectance panels, requires that the control targets are at least four times the size of the sensor's point spread function (PSF) full width at half maximum (FWHM) in order to avoid errors due to the contrast loss from the sensor's modulation transfer function (MTF). For many sensor systems, this requires the targets to be five to seven time larger than the sensor's ground sample distance (GSD) in order for the reference panels to be larger than the sensor's radiometrically accurate instantaneous field of view (RAIFOV). In this presentation, a new mirror-based empirical line method (MELM) is introduced that allows the reflectance reference targets to be much smaller, even subpixel in size and avoid the MTF errors associated with diffuse panels . The key to this approach is the application of an algorithm that converts the specular reflectance of the convex mirrors, used in the reflectance panels, to an effective Lambertian reflectance factor as recorded by the sensor. The application will be demonstrated for the difficult challenge of applying an ELM method to water surfaces. The results will be presented for the reflectance calibration of water scenes recorded by a NASA Glenn Research Center airborne hyperspectral sensor in the study of cyanobacteria algal blooms in the western Lake Erie basin

*Stephen Schiller an adjunct professor in the Physics Department at South Dakota State University involved in mentoring and collaboration with students and faculty in the SDSU Image Processing Lab. He was a co-founder (with Dennis Helder) of the vicarious calibration program at South Dakota State University supporting numerous NASA and USGS remote sensing programs including the NASA/JACIE Commercial Satellite Calibration program starting in 2000/2001. Stephen also supports an active research and development program as a calibration scientist at Raytheon Space and Airborne Systems, El Segundo, CA developing in-flight calibration and validation methods for space-based and airborne imaging systems. This includes both on-board and vicarious methods for a wide range of earth observing systems. Stephen received his Ph.D. in Astrophysics from the University of Calgary, Canada; M.S. degree in Astronomy from Ohio State University and a B.S. degree in Physics from Walla Walla University*

## DooChun Seo- Korea Aerospace Research Institute

**Geometric accuracy improvement through Long-term bias compensation in KOMPSAT-3**

KOMPSAT-3 was successfully launched on May 18th, 2012. It with high resolution optical satellite has been thoroughly tested, calibrated and validated during LEOP (Launch & Early Operation Period) by KARI.

The geometric calibration consists of two phases. At phase I, AOCS (Attitude and Orbit Control Subsystem) in-orbit calibration is performed with the satellite's position and attitude data estimated through time synchronization of GPS, AOCS, and payloads. Phase II includes the calibration of CCD alignments and the focal length, the CCD overlap area correction, band-to-band alignments. The main quality parameters of image data is MTF, SNR, location accuracy. The result of image data quality, MTF is 6~8%, SNR is 90~120, location accuracy is 30m ~ 60m.

In this paper, we introduce KOMPSAT-3 the physical sensor model that incorporates the interior and exterior orientation parameters. Based on the rigorous sensor model, the location accuracy of KOMPSAT-3 will be introduced from October 2015 to March 2017. Bias compensation will be explained using bore-sight calibration method base on long-term location accuracy characteristics. Finally the location accuracy after the calibration is presented.

*Dr. DooChun Seo received the Ph.D. degree in civil engineering from Gyeongsang National University, Korea, in 2002.He has been at Korea Aerospace Research Institute since 2002, and has been a Principal Researcher of Satellite Cal/ Val Department since 2005. His primary research interests and back ground are in satellite photogrammetry, sensor modeling, DEM, Ortho-image generation, image processing and geometric calibration of high resolution satellite image data*

## Byron Smiley-Planet

**Correcting the Absolute Geolocation Accuracy of SkySat Orthos at Planet**

When Planet acquired Terra Bella in April 2017, the Google image processing infrastructure was not part of the transaction. A new Planet production system had to be built to prepare SkySat imagery for sale to customers. Just like the previous Google production system, a crucial processing step is the correction of absolute geolocation error by registration to a base layer.

Geometric monitoring of the production pipeline is essential for best performance. It's important to use different absolute references like GCPs that are wholly independent of the base layer when evaluating performance, otherwise the correction appears "perfect" with zero error. Independent monitoring discovers and corrects geometric problems that would otherwise be found by customers if they performed their own GCP measurements.

We will present the efficacy of Planet's SkySat image processing system, with emphasis on GCP measurements that examine the registration to the base layer. We will quantify the improvement in georeferencing for an older, A generation satellite (SkySat-1 or 2), as well as a newer, C class generation satellite (SkySat-3, 4, 5, 6, or 7).

A direct comparison of the uncorrected CE90s between the A and C generation will be possible, which will demonstrate the improved attitude determination capabilities of the C class.

*Dr. Byron Smiley has been in the commercial remote sensing industry for the last 13 years. His current position of Calibration Scientist at Planet started back in April 2017 when Terra Bella was acquired from Google. Prior to that, he worked at Terra Bella throughout its existence (2014-2017), and the final year of the predecessor startup Skybox Imaging (2013-2014). During that time, he performed the initial geometric calibrations for all the Skysats, like aligning the camera boresights and fitting the interior orientations. Before that, he had a brief stint at BAE (2011-2013) where he worked on video tracking algorithms. This was preceded by employment at DigitalGlobe (2004-2011), where he participated in the calibration campaigns of WorldView-1 and 2.*

*He's excited to continue his geometric calibration work under Planet leadership, which involves measuring the CE90 of all the Skysats and keeping them in spec. He will have a busy future at Planet, because they have three constellations of different satellites.*

## Ellyne Kinney Spano-Planet

**SkySat Radiometric Calibration Assessment and Early Result**

In early 2017 Planet acquired Terra Bella and the SkySat constellation of high-resolution imaging satellites. The SkySat constellation fleet will provide rapidly updated 1 meter resolution images of select areas of the globe to complement the daily 3-5 meter resolution imagery produced by the Dove and Rapid Eye constellations. To support these expanded data offerings the SkySat Radiometric Calibration program will evolve from an uncalibrated visual product to a calibrated, top-of-atmosphere Radiance (TOAR) and top-of-atmosphere reflectance product. Here we present an assessment of SkySat radiometry, i.e. sensor noise, linearity, stability and an initial assessment of absolute accuracy. To assess these properties we will use a combination of pre-flight calibration data and on-orbit cross-comparisons of SkySat and RapidEye images over calibration sites at Brooking, SD and Railroad Valley, NV. Additionally, we will present a preliminary set of absolute radiometric calibration coefficients for the Multispectral bands and a roadmap for future development of the SkySat radiometric calibration.

*Ellyne has 25 years' experience calibrating sensors for space based science missions. She is excited to join Planet as part of Planet's acquisition of Terra Bella/Skybox Imaging. Her previous role at Terra Bella was leading the Image Chain Commissioning of the gen C SkySat constellation.*
*Prior to joining Terra Bella, Ellyne worked at the University of Arizona's Lunar and Planetary Lab developing the L1B Image processing algorithms and supporting the pre-flight calibration for the OSIRIS-REx Camera Suite for the OSIRIS-REx Asteroid Sample Return mission. Other calibration projects include participating in pre-flight and in-flight calibration for the Space Telescope Imaging Spectrograph (STIS) and the in-flight geometric calibration of the Wide-Field Planetary Camera (WF/PC-I) and Wide-Field Planetary Camera 2 (WFPC2) on the Hubble Space telescope mission*

## James Storey-USGS-EROS/SGT Inc

**Landsat-8/Sentinel-2 Registration Accuracy and Improvement Status**

The Landsat-8 and Sentinel-2 sensors provide multi-spectral image data with similar spectral and spatial characteristics that together provide improved temporal coverage globally. Both systems are designed to register Level 1 products to

*Mr. Storey has degrees from Cornell University (BS), the University of Wisconsin-Madison (MS), and the Johns Hopkins University (MS). He has more than thirty-six years of experience designing and implementing sensor data analysis and calibration, image processing, and photogrammetric exploitation systems for the extraction of information from aerial photography and digital satellite imagery. His particular areas of expertise include image geolocation/satellite photogrammetry, sensor geometric calibration and characterization, on-orbit modulation transfer function estimation, and image processing. Mr. Storey is currently a calibration scientist responsible for the geometric calibration and characterization of the Landsat-8 Operational Land Imager (OLI) and Thermal InfraRed Sensor (TIRS) instruments.*

a reference image framework, however, the Landsat-8 framework, based upon the Global Land Survey (GLS) images, contains residual geolocation errors leading to predicted sensor-to-sensor misregistration of 26 meters (2σ). Direct registration measurements yield results generally consistent though slightly better than the prediction. The Landsat framework is being readjusted for consistency with the Sentinel-2 Global Reference Image (GRI). This readjustment includes several elements: 1) Densifying the GLS control framework spatially and temporally by extracting additional control points from Operational Land Imager data; 2) Performing an initial global triangulation of the new and existing control points using Landsat 8 data; and 3) Performing a final triangulation that includes tie points extracted from Sentinel-2 Multi Spectral Instrument data products to link the readjusted Landsat-8 control points to the Sentinel-2 GRI reference framework. Completion of this activity is expected in 2018, at which point the readjusted GLS control will be used in a complete Collection-2 reprocessing of the entire Landsat archive.

## Mustafa Teke- TUBITAK UZAY Space Technologies Research Institute

### Experiences in Developing Satellite Image Processing Workflow for RASAT and GÖKTÜRK-2

As a newcomer in space technologies TÜBİTAK UZAY built RASAT and Göktürk-2 earth observation satellites. RASAT has a resolution of 7.5 m while Göktürk-2 has higher resolution of 2.5 meters.

TÜBİTAK UZAY has the ability to produce high resolution LEO satellites, it also developed its own satellite image processing capabilities based on image processing and computer vision.

In this paper, the workflow of automated satellite image processing chain for images acquired by RASAT and Göktürk-2 satellites are described. Automated satellite image processing chain include radiometric calibration, MTF sharpening, band registration, flare correction, georeferencing, orthorectification, pansharpening, color enhancement and edge sharpening. Careful design and application of these steps are crucial to retain an acceptable level of radiometric and geometric accuracy as well as visual quality for use with various applications. Results of automatic image processing for RASAT are disseminated via GEZGİN Geoportal (https://www.gezgin.gov.tr)

Notable contributions of this study are a new color enhancement method, a new pansharpening algorithm and automatic georeferencing method of images using Landsat 8 as a reference.

*Mustafa Teke received his B.Sc. degree in electrical and electronics engineering in 2005 and M.Sc. degree in 2010 information systems both from Middle East Technical University. During his M.Sc. thesis, he worked on multi-spectral satellite imagery band registration. He is currently working towards Ph.D. degree at Information System, Middle East Technical University, His Ph.D. thesis subject is classification of vegetation using hyperspectral images. He currently works at TÜBİTAK UZAY (The Scientific and Technological Research Council of Turkey, Space Technologies Research Institute) as a senior researcher in Remote Sensing Group. His main research topics are remote sensing, satellite image processing, pattern recognition, computer vision. He has worked on the projects that are related with satellite image processing. He was working in the related projects as project manager, system designer and software developer. He developed satellite image processing algorithms for RASAT and Göktürk-2 satellites. He is currently working on hyperspectral image processing for precision agriculture.*

## Kurt Thome, *NASA*

**Radiometric Calibration of Aster Using Automated In-Situ Measurements**

Automated measurement approaches for reflectance-based calibration offer an opportunity for government researchers to assess the radiometric quality without the need to coordinate satellite acquisitions with ground-based field campaigns. The advantage to in-situ measurements is that they lead to a well-demonstrated and traceable accuracy. The accuracy of the results from these automated sites makes them suitable for harmonizing the radiometric output from multiple sensors. Results are shown here from Terra's ASTER visible and near infrared telescope to demonstrate the utility of automated sites for radiometric quality assessment. Plans for use of automated data for assessment of other sensors in use by other government agencies is discussed.

*Kurt Thome obtained a BS degree in Meteorology from Texas A&M University and MS and PhD degrees in Atmospheric Sciences from the University of Arizona. He then joined what is now the College of Optical Sciences becoming full professor in 2006. He served as the Director of the Remote Sensing Group from 1997 to 2008. Thome moved to NASA's Goddard Space Flight Center in 2008 as a Physical Scientist in the Biospheric Sciences Branch. He has been a member of the Landsat-7, ASTER, MODIS, and EO-1 Science Teams providing vicarious calibration results for those and other imaging sensors. He is the Vice Chair of CEOS' Working Group on Calibration and Validation and is a Fellow of SPIE. Thome served as the calibration lead for TIRS on Landsat 8, is Deputy Project Scientist for CLARREO for which he is also the instrument lead for the Reflected Solar Instrument, Instrument Scientist for VIIRS, and Project Scientist for Terra.*

## Dmitry L. Varlyguin- GDA Corp

**Assessment of the Radiometric Calibration of PlanetScope 2 Dove Imagery**

We have undertaken a radiometric calibration study of Planet Dove imagery from the PlanetScope 2 constellation. The goal of the study was to assess the radiometric calibration of the PlanetScope 2 L3B imagery by cross-comparing it with "gold" standard Landsat 8 data. TOA (top-of-atmosphere) reflectance calibrated PlanetScope 2 imagery was found to exhibit high correlation with co-incident / co-located Landsat 8 TOA reflectance calibrated imagery. High correlation was observed across all analyzed locations, dates, PlanetScope 2 sensors, bands, and land cover types. For bright pseudo-invariant sites a small but measurable and repeatable variability in TOA reflectances was observed per PlanetScope 2 orbit (Sun-Synchronous Orbit v International Space Station orbit), satellite, and spectral band. PlanetScope 2 radiometric calibration may be further improved by imagery calibration to the surface reflectances and cross-calibration with surface reflectances calibrated "gold" standard imagery.

*Dmitry Varlyguin is Vice President & Chief Scientist at GDA Corp since 2004. He has over 25 years of experience working in Remote Sensing with GIS and image processing systems and a range of commercial and public remotely sensed data. His research interests include: automated analysis of Remotely Sensed data, combined spectral, spatial, and contextual image processing, and the design of iterative, self-learning expert systems. Dr. Varlyguin received his B.S. and M.S. from Moscow State University and his Ph.D. from Clark University in Worcester, MA.*

## Nicholas Wilson-Planet

**Absolute Radiometric Calibration of the Planet Dove Satellites**

Planet operates the world's largest constellation of Earth Observation satellites, with over 140 satellites in orbit. The satellites, known as Doves, are operated in non-tasking and nadir pointing mode and have a Bayer Masked CCD sensor that captures imagery in VNIR bands with 3-5 meter resolution, depending on orbit parameters. With the large numbers of satellites, traditional vicarious field campaigns do not scale due to the time and resources such fieldwork requires. An automated approach for on-orbit radiometric calibration was required given the operational behavior of the constellation. The approach utilizes a hybrid methodology to combine lunar calibration and cross calibration to enable on-orbit absolute radiometric calibration of each individual Dove satellite. The cross-calibration approach uses instantaneous crossovers in spectrally characterized pseudo-invariant calibration sites with RapidEye, Sentinel 2, Landsat8, and other Dove satellites. Lunar Calibration utilizes an implementation of the ROLO model [1] and daily moonshots taken by each satellite during both the waxing and waning moon phases. The automated process is fully implemented in Python and operates in Planet's cloud infrastructure. Using modern software practices and relying on automation has allowed for temporal monitoring of a large constellation of satellites and the ability to apply regular updates to maintain absolute radiometric calibration of each satellite. Initial validation using 36 Dove satellites shows an uncertainty of 5-6% at 1-sigma is achieved across all satellites using RadCalNet vicarious collects as a validation dataset. In this presentation, we describe the experience of developing the automated absolute radiometric calibration approach and the results of the on-going calibration effort.

*Nicholas Wilson is the team lead for the Calibration and Validation team at Planet. Nick is responsible for developing calibration strategy and roadmaps, designing the automated calibration infrastructure, and leading a team of scientists and engineers whose primary responsibility is the radiometric calibration of the Dove Satellites. He is a geographer by training with a specialization in remote sensing, geostatistics, and software development. He received his Master's degree from Clark University in Geographic Information Science*

## Terrance Yee-Astro Digital/Parabilis Space Technologies

**"Key Elements of Calibration for High Quality Data in the Landmapper CubeSat Missions"**

Most technology demonstration or university imaging CubeSast place less emphasis on instrument calibration, due to funding limitations and focus on factors other than science quality. A traditional flagship-class science mission typically places an extraordinary emphasis on calibration and achieving very high radiometric and geometric precision and accuracy, often devoting a significant portion of the budget to employ multiple approaches to ensure the best possible cross correlations. The Landmapper mission has a mission budget between these two extremes with a focused commercial objective of obtaining the best scientific data quality possible while operating with low enough costs to make the products widely available to the public. The Landmapper approach emphasizes fast development cycles and a lean set of tools and people, enabling a low-cost result. The calibration campaign keeps the cornerstones of traditional calibration intact to produce high quality data that maximizes utility of the products but takes a very streamlined approach in developing the radiometric and geometric artifacts employed in the image processing chain. Calibration starts with ground based sensor response characterization which is used to optimize imaging parameters before launch and forms the basis for the initial calibration coefficients. On orbit, Simultaneous Nadir Observations (SNO) with Landsat 7 and 8 are key elements which exploit the Landmapper's deliberate similarity to these instruments and take advantage of the exquisite calibration programs run by the Landsat team to produce an absolute radiometric calibration. This is combined with ground observations of Pseudo-Invariant Calibration Sites and a simultaneous ground measurement campaign that again takes advantage of the work already being done for Landsat. Relative calibration between the Landmapper satellites will also focus on SNO and PICS inputs. Flat field imaging of both bright and dark sources will be utilized to map out detector pixel to pixel variations and will utilize deliberate ground blur and rapid multi-shot imaging to achieve maximum effectiveness. Lunar calibrations will also be employed during the times when the moon is near full and compared to other methods to evaluate utility. All this data will feed into the calibration coefficient matrix in a weighted fashion and pass through several automated and manual quality checks prior to incorporation and update. The use of machine learning and automated processing is maximized to keep operational expenses at a minimum. Ongoing calibration and prior imaging data are used to tune image taking parameters such as exposure at the individual daily image level to ensure maximum signal to noise ratio without significant detector saturation. The initial calibration campaign and spacecraft commissioning phase will take 3 months. Routine calibration activity throughout the satellite lifetime will be scheduled after careful examination of the stability trends from the commissioning phase and during ongoing operations of the prototype vehicles being launched in July of 2017. This approach produces scientific quality imagery at a pace and price that is unparalleled.

*Mr. Yee has 27 years of experience in Aerospace Engineering. His expertise is focused in Spacecraft Systems Engineering with knowledge of all phases of development from conceptual design, detailed design, fabrication, integration and test, launch and flight operations. He has served as Chief Engineer for five spacecraft, Integration and Test Lead for four spacecraft, Program Manager for a spacecraft and a launch vehicle, and has had a lead role in flight operations on five missions. His current assignments include preparing the Landmapper constellation for deployment and operations and serving as power systems lead for the NASA CYGNSS mission. He also serves as the director of new business development and has lead or contributed to dozens of proposals. Mr. Yee has a BS in Aerospace Engineering from UCLA and an MS in Aerospace Engineering from the University of Colorado.*

## Ignacio A Zuleta- Planet Labs, Inc.

**Automated Image Quality assessment in a large mixed constellation of earth-imaging satellites**

Planet Labs, Inc. operates a large mixed constellation that includes spacecraft ranging from 1 meter resolution to 6 meter resolution. In order to monitor these sats we have pioneered the development of automated metrics as well as systematically identified and addressed image quality issues present in our early hardware builds. Here we present an overview of the general state of the art in image quality across all sats, focusing on data from our Dove platform but extending the overview to SkySat and RapidEye constellations. We also discuss general trends in SNR, image sharpness and image defects.

*Originally trained as Physical Chemist, Dr. Ignacio A. Zuleta got his BS/MS at University of Buenos Aires, Argentina. He later obtained a Doctorate in Physical Chemistry at Stanford University where he developed instrumentation for monitoring chemical dynamics using newly developed imaging sensors and ion optics. During his postdoctoral fellowship at University of California, San Francisco he developed optical instrumentation for the monitoring of gene expression. He has co-authored numerous many peer-reviewed publications and conference presentations. At Planet Labs, Inc. he has led the development of image quality metrics and payload commissioning as well as the development of several spacecraft sub-systems including the camera system. He currently serves as Director of the Imaging Group which encompasses payload operation and development, radiometric calibration, image quality monitoring as well as general imagery product development.*